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SEMICONDUCTOR DEVICE

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ABSTRACT:

PURPOSE: To realize an electron wave interference effect so as to enable a semiconductor to be easily manufactured by a method wherein N-type semiconductor regions disposed at intervals of electron de Broglie wavelengths are formed just under a gate electrode on the surface of a carrier feed layer, the length of the gate electrode in a source-drain direction is set smaller than an electron inelastic scattering length, and a Schottky electrode is formed on the rear side of a semiconductor substrate.

CONSTITUTION: A Schottky electrode (back gate electrode) 8 is formed on the rear side of a non-doped GaAs substrate 1 through evaporation. A source electrode 6S and a drain electrode 6D are formed on an N-type GaAs layer 5 through evaporation and subjected to an alloy treatment so as to come into ohmic contact with external leads. A region of the N-type GaAs layer 5 surrounded with the source electrode 6S and the drain electrode 6D is partially removed through an electron beam lithography method to form a stripe pattern where N-type GaAs fine wires which are 300 $\text{\AA}$ ; or so in width, disposed at intervals of 300 $\text{\AA}$ ; or so, and whose longitudinal direction extends in a source-drain direction. Gate electrodes (Schottky electrodes) 7 500 $\text{\AA}$ ; or so in gate length are formed on a stripe pattern composed of N-type GaAs fine lines through an EB lithography method.

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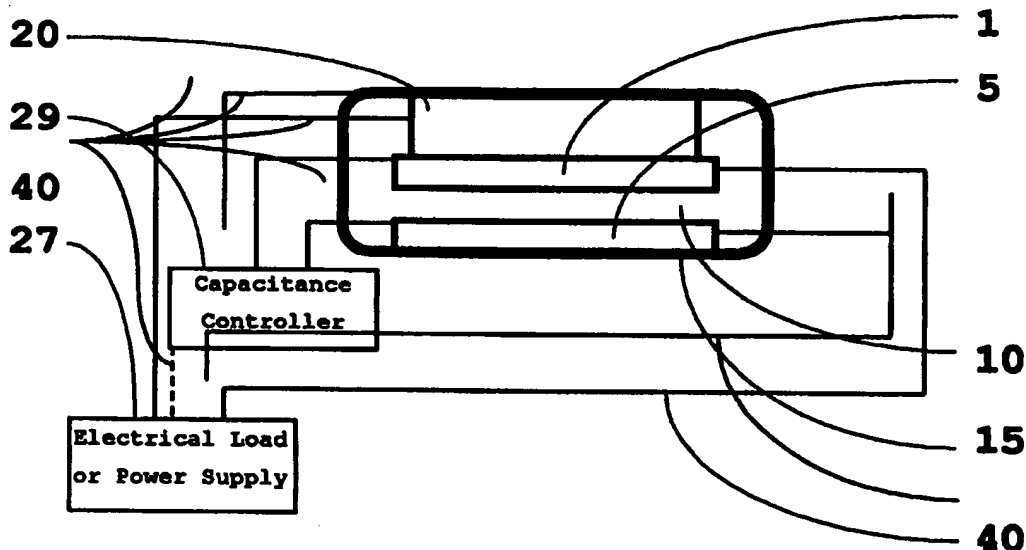
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(54) Title: DIODE DEVICE



(57) Abstract

Diode devices are disclosed in which the separation of the electrodes (1, 5) is set and controlled using piezo-electric, electrostrictive, or magnetostrictive actuators (20). This avoids problems associated with electrode spacing changing or distorting as a result of heat stress. In addition it allows the operation of these devices at electrode separations which permit quantum electron tunneling between them. Pairs of electrodes whose surfaces replicate each other are also disclosed. These may be used in constructing devices with very close electrode spacings.

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## Diode Device

### Technical Field

The present invention is related to diode devices, in particular, to diode devices in which the separation of the electrodes is set and controlled using  
5 piezo-electric, electrostrictive or magnetostrictive positioning elements. These include thermionic converters and generators, photoelectric converters and generators, and vacuum diode heat pumps. It is also related to thermotunnel converters.

### Background Art

#### 10 Thermionic Generators

One form of thermionic vacuum diode is the thermionic converter. A problem associated with the design of these is the space-charge effect, which is caused by the electrons themselves as they leave the cathode. The emitted  
15 electrons have a negative charge that deters the movement of other electrons towards the anode. Theoretically the formation of the space-charge potential barrier may be prevented in at least two ways: positive ions may be introduced into the cloud of electrons in front of the cathode, or the spacing between the electrodes may be reduced to the order of microns.

The use of positive ions to reduce space charge is not without problems.  
20 Although cesium and auxiliary discharge thermionic converters have been described, they do not have high efficiency, are costly to fabricate, and, particularly in the high-pressure ignited mode, do not have a long life. The technique of introducing a cesium plasma into the electrode space brings with it further disadvantages. These include heat exchange reactions within the  
25 plasma during the operation of the device, and the reactivity of the plasma, which can damage the electrodes.

Although Fitzpatrick (U.S. Pat. No. 4,667,126) teaches that "maintenance of such small spacing with high temperatures and heat fluxes is a difficult if not impossible technical challenge", in an article entitled "Demonstration of  
30 close-spaced thermionic converters", 28<sup>th</sup> Intersociety Energy Conversion Engineering Conference, Vol. 1, pages 1573 - 1580, he goes on to disclose a close spaced thermionic energy converter which operates at temperatures of 1100 to 1500 K at a variety of cesium pressures. Electrodes are maintained at a separation of the order of 10  $\mu$ m by 3 ceramic spacers mounted on the  
35 collector. With electrodes at 1300 and 800 K, conversion efficiencies of

-2-

11.6% were obtained. It utilizes advanced monocrystal materials to achieve reliable operation and long life, and produces a reasonable output power with good efficiency at lower temperatures where typical ignited mode devices would produce no useful power at all. It is therefore useful at the bottom  
5 end of cascaded thermionic systems, with a very high temperature barium-cesium thermionic converter at the top end.

To operate a converter with a gap spacing of less than 10  $\mu\text{m}$ , the electrode surface must be very flat and smooth, with no deformation larger than about 0.2  $\mu\text{m}$ . This places a limitation on the practical size of electrodes for the  
10 emitter and collector, because heat flux through the surfaces causes a differential thermal expansion from one side relative to the other, leading to thermal expansion-caused deformation into a "dome-like" shape. This issue is even more important in high power operation. Although this deformation can be tolerated if the diameter of the electrodes is very small, the devices  
15 described by Fitzpatrick have diameters of several centimeters. Another issue is degradation of the in-gap spacers at high emitter temperatures.

Fitzpatrick addresses both these in a later paper, entitled "Close-spaced thermionic converter with active control and heat-pipe isothermal emitters", 31<sup>st</sup> Intersociety Energy Conversion Engineering Conference, Vol. 2, pages 920  
20 - 927. He proposes a device having a large isothermal emitter, utilizing a heat pipe built into its structure with a single crystal emitting surface. The proposed device avoids degradation of the in-gap spacers at high emitter temperatures by using active spacing control, utilizing piezo electric actuators in conjunction with feedback control for continuously adjusting the  
25 gap size.

The proposed device, however, is relatively large, expensive and not amenable to mass-production. There remains a need, therefore, for a thermionic generator that is easy to fabricate, inexpensive, reliable, of high efficiency, modular, compact and having an extended life.

30 For example, the alternator of the automobile could be replaced by a thermionic generator using the heat contained in the exhaust gases as a source of energy, which would lead to an increase in the efficiency of the engine. Svensson and Holmlid, in their paper entitled: "TEC as Electric Generator in an Automobile Catalytic Converter" 31<sup>st</sup> Intersociety Energy  
35 Conversion Engineering Conference, Vol. 2, pages 941 - 944, propose the possible use of carbon covered electrodes which become coated with Rydberg matter, resulting in the reduction of the interelectrode distance. They report that such a device might be expected to have an efficiency of 25 - 30% at temperatures of 1500 - 1600 K. To obtain the high temperatures required, a

-3-

fuel mixture would be injected into the device. Different configurations are discussed, but it is not clear how such a device would be economically constructed.

Another application is in domestic and industrial heating systems. These  
5 need a pump to circulate heated water around the system, which requires a source of power. The control circuitry regulating the temperature of the building being heated also requires power. These could both be supplied by means of a thermionic generator powered by the hot flue gases.

A further application utilizes heat generated by solar radiation. This could  
10 either be in space or earth-based solar power stations, or on the roof of buildings to supply or augment the power requirements of the building.

In Edelson's Patent Application, filed 1997 January 27, titled "Method and Apparatus for Thermionic Converter", serial number 08/790,753, assigned to the same assignee as the present invention, and incorporated herein in its  
15 entirety by reference, a thermionic converter having close spaced electrodes is disclosed which is fabricated using micromachining techniques. This device addresses many of the problems described above, particularly those relating to economic fabrication and how to achieve close spaced electrode design. However, in operation, temperature differences between the hot  
20 emitter and cooler collector may cause high thermal stresses leading to the shape of the region between the electrodes being altered.

The present invention extends the robustness of Edelson's previous device without detracting from its ease and economy of fabrication by allowing it actively to respond to these high thermal stresses by means of active  
25 piezoelectric, electrostrictive or magnetostrictive elements incorporated to produce a micro-electromechanical thermionic converter.

#### **Thermotunnel Converter**

The thermotunnel converter is a means of converting heat into electricity that uses no moving parts. It has characteristics in common with both  
30 thermionic and thermoelectric converters. Electron transport occurs via quantum mechanical tunneling between electrodes at different temperatures. This is a quantum mechanical concept whereby an electron is found on the opposite side of a potential energy barrier. This is because a wave determines the probability of where a particle will be, and when that  
35 probability wave encounters an energy barrier most of the wave will be reflected back, but a small portion of it will 'leak' into the barrier. If the barrier is small enough, the wave that leaked through will continue on the other side of it. Even though the particle does not have enough energy to

-4-

get over the barrier, there is still a small probability that it can 'tunnel' through it.

The thermotunneling converter concept was disclosed in U.S. Patent No. 3,169,200 to Huffman. In a later paper entitled "Preliminary Investigations of a Thermotunnel Converter", [23rd Intersociety Energy Conversion Engineering Conference vol. 1, pp. 573-579 (1988)] Huffman and Haq disclose chemically spaced graphite layers in which cesium is intercalated in highly orientated pyrolytic graphite to form a multiplicity of thermotunneling converters in electrical and thermal series. In addition they teach that the concept of thermotunneling converter was never accomplished because of the impossibility of fabricating devices having electrode spacings of less than 10  $\mu\text{m}$ . The current invention addresses this shortcoming by utilizing one or more piezo-electric, electrostrictive or magnetostrictive elements to control the separation of the electrodes so that thermotunneling between them occurs.

A further shortcoming of the devices described by Huffman is thermal conduction between the layers of the converter, which greatly reduces the overall efficiency of these thermotunnelling converters.

#### Photoelectric Converter

In Edelson's application filed 12th May 1997, titled "Method and Apparatus for Photoelectric Generation of Electricity", serial number 08/854,302, assigned to the same assignee as the present invention, and incorporated herein by reference, is described a Photoelectric Generator having close spaced electrodes separated by a vacuum. Photons impinging on the emitter cause electrons to be emitted as a consequence of the photoelectric effect.

These electrons move to the collector as a result of excess energy from the photon: part of the photon energy is used escaping from the metal and the remainder is conserved as kinetic energy moving the electron. This means that the lower the work function of the emitter, the lower the energy required by the photons to cause electron emission. A greater proportion of photons will therefore cause photo-emission and the electron current will be higher. The collector work function governs how much of this energy is dissipated as heat: up to a point, the lower the collector work function, the more efficient the device. However there is a minimum value for the collector work function: thermionic emission to the collector will become a problem at elevated temperatures if the collector work function is too low.

Collected electrons return via an external circuit to the cathode, thereby powering a load. One or both of the electrodes are formed as a thin film on a transparent material, which permits light to enter the device. A solar

-5-

concentrator is not required, and the device operates efficiently at ambient temperature.

#### **Vacuum Diode-Based Devices**

In Edelson's disclosure, filed 1995 July 5, titled "Method and Apparatus for Vacuum Diode Heat Pump", serial number 08/498,199, assigned to the same assignee as the present invention, incorporated herein in its entirety by reference, a new use for thermionic vacuum diode technology is disclosed wherein a vacuum diode is constructed using very low work function electrodes. A negative potential bias is applied to the cathode relative to the anode, and electrons are emitted. In the process of emission, the electrons carry off kinetic energy, carrying heat away from the cathode and dissipating it at an opposing anode. The resulting heat pump is more efficient than conventional cooling methods, as well as being substantially scalable over a wide range of applications. Fabrication using conventional techniques is possible.

#### **Piezoelectric Positioning Elements**

Piezoelectric worm-type shifting mechanisms, or piezo motors, can move extremely short distances of the order of a single Angstrom, while having a stroke of several tens of millimeters.

Scanning Tunneling Microscopes are well known for employing piezoelectric devices to maintain tip distance from a surface to an accuracy of 1 angstrom. U.S. Pat. No. 4,423,347 to Kleinschmidt et al. discloses a type of electrically actuated positioning element formed of piezo-electric bodies, which may, for example, be used to operate a needle valve.

U.S. Pat. No. 5,351,412 to Furuhashi and Hirano discloses a device that provides micro-positioning of the sub-micron order.

U.S. Pat. No. 5,049,775 to Smits discloses an integrated micro-mechanical piezo-electric motor or actuator. This has two parallel cantilever beams coated with a piezo-electric material and attached to a body to be moved at one end, and to a V-shaped foot at the other. By applying an electric field, the foot may be raised, twisted, lowered and straightened, providing movement. An example has a device with cantilever beams  $1 \times 10 \times 200 \mu\text{m}$ , which can move at 1 cm/s.

The above illustrate that piezo-electric elements may be fabricated and used at micron and sub-micron scale and that they are useful for positioning objects with great accuracy. Fitzpatrick takes advantage of these features



-6-

in his proposed close spaced thermionic converter. He does not teach, however, that micro-mechanical devices such as that disclosed by Smits may be adapted to form a useful function in positioning the electrodes in a micromachined thermionic vacuum diode.

5 **Electrostrictive and Magnetostrictive Positioning Elements**

Razzaghi (U.S. Pat. No. 5,701,043) teaches that some commercially available magnetostrictive materials readily produce strains 10 times higher than that of electroactive materials such as piezoelectric or electrostrictive elements. They are also superior with respect to load, creep, sensitivity to  
10 temperature and working temperature range. He discloses a high-resolution actuator using a magnetostrictive material able to achieve displacements with subnanometer resolution and a range of about 100  $\mu\text{m}$ .

Visscher (U.S. Pat. No. 5,465,021) disclose an electromechanical displacement device which uses piezoelectric, electrostrictive or magnetostrictive  
15 clamping and transport elements.

Takuchi (U.S. Pat. No. 5,592,042) disclose a piezoelectric or electrostrictive actuator of bi-morph or uni-morph type, and teach that it may be useful as a displacement controllable element, an ink jet ejector, a VTR head, a switching element, a relay, a print head, a pump, a fan or  
20 blower.

Kondou (U.S. Pat. No. 5,083,056) disclose an improved circuit for controlling a bimorph-type electrostriction actuator.

Hattori (U.S. Pat. No. 4937489) disclose an electrostrictive actuator for controlling fine angular adjustments of specimens under microscopic scrutiny.

25 **Surface Polishing**

It is known to the art that over a 1 cm distance length, a surface can be polished to a fraction of a micron. However, the art provides no methods for providing surfaces that are flat to the order of tens of angstroms.

Additionally, the art provides no methods of making electrodes that match  
30 each other's surface features, thus providing 2 surfaces which are flat relative to one another. The present invention discloses and claims such a technique, which allows for very close spacing between electrodes.

**Disclosure of Invention**

The present invention discloses, in one preferred embodiment, a Gap Diode  
35 fabricated by micromachining techniques in which the separation of the

-7-

electrodes is controlled by piezo-electric, electrostrictive or magnetostrictive actuators. Another preferred embodiment is a Gap Diode built and operated by MicroEngineeringMechanicalSystems, or MEMS, and its equivalents, in which the separation of the electrodes is controlled by

5 piezo-electric, electrostrictive or magnetostrictive actuators.

The present invention further discloses a Gap Diode in which the separation of the electrodes is controlled by piezo-electric, electrostrictive or magnetostrictive actuators. Preferred embodiments include Cool Chips, Power Chips, and photoelectric converters. In further embodiments, Gap Diodes may

10 be fabricated using micromachining techniques, and include MicroEngineeringMechanicalSystems, or MEMS versions, or their equivalents, in which the electrode separation is controlled by piezo-electric, electrostrictive or magnetostrictive actuators.

In a further embodiment, the present embodiment Gap Diodes in which the

15 separation of the electrodes is controlled by piezo-electric, electrostrictive or magnetostrictive actuators, and where the space between the electrodes is filled with an inert gas: according to this embodiment the separation of the electrodes is less than the free mean path of the electrons in the inert gas. This means that thermal conduction between the electrodes

20 is almost entirely eliminated.

In operation, temperature differences between the emitter or cathode electrode, and the collector or anode electrode, of the Gap Diode may cause high thermal stresses leading to the space between electrodes being altered. These thermal stresses may also cause the electrodes to flex, buckle or

25 otherwise change their shape. The present invention addresses these problems by utilizing a piezo-electric, electrostrictive, or magnetostrictive element to control the separation of the electrodes. Furthermore the present invention discloses utilizing a piezo-electric, electrostrictive, or magnetostrictive element to alter the shape of the electrodes to overcome

30 flexing, buckling or shape-changing thermal stresses.

The present invention further discloses a method for fabricating a pair of electrodes in which any minor variations in the surface of one electrode are replicated in the surface of the other. This permits the electrodes to be spaced in close proximity.

35 A method of selecting materials is disclosed which can be used to compensate for thermal expansion. This method is optimal for use in thermotunneling Power Chips and Cool Chips, and also has uses in especially close-spaced thermionic Power Chips and Cool Chips.

-8-

The present invention further discloses the concept of employing electron tunneling in a Cool Chip.

These devices overcome disadvantages of prior art systems such as economy and ease of fabrication and problems introduced by heat distortion at high  
5 temperature operation.

The present invention comprises one or more of the following objects and advantages:

It is an object of the present invention to provide Gap Diodes or Power Chips or Cool Chips in which the separation of the electrodes is controlled by  
10 piezo-electric, electrostrictive or magnetostrictive actuators.

An advantage of the present invention is that alterations to the spacing of the electrodes that may happen as a consequence of the large temperature difference between the electrodes may be nullified.

A further advantage of the present invention is that a less demanding  
15 manufacturing specification is required.

A further advantage of the present invention is that the resulting Gap Diode will be extremely resistant to vibration and shock, as the actuators can rapidly counteract any such stresses.

It is a further object of the present invention to provide Power Chips or  
20 Cool Chips or Gap Diodes in which the separation of the electrodes is reduced to micron or sub-micron distances, and is maintained at this small distance through the action of piezo-electric, electrostrictive or magnetostrictive actuators.

An advantage of this invention is that space charge effects are reduced.

25 Another advantage of this invention is that changes in electrode separation due to thermal changes occurring as the device is operated may be compensated.

It is a further object of the present invention to provide Gap Diodes or Cool Chips or Power Chips in which the separation of the electrodes is small  
30 enough to allow electrons to tunnel between cathode and anode, and in which this small separation between electrodes is maintained through the action of piezo-electric, electrostrictive or magnetostrictive actuators.

An advantage of this invention is that the efficiency of the inter-converter is substantially increased.

35 An advantage of this invention is that heat can be efficiently pumped from one electrode to another.

-9-

An advantage of this invention is that a temperature differential can be used to generate electricity.

An advantage of this invention is that a low work function electrode is not required.

- 5     An advantage of this invention is that, when it is used to pump heat, it can cool down to 1 degree Kelvin.

It is a further object of the present invention to provide Gap Diodes in which the separation of the electrodes is less than the free mean path of an electron, and in which this small separation between electrodes is maintained  
10    through the action of piezo-electric, electrostrictive or magnetostrictive actuators.

An advantage of this invention is that the space between the electrodes may be filled with an inert gas.

- 15    An advantage of this invention is that thermal conduction between the electrodes is substantially reduced, and the efficiency of the device is substantially increased.

It is a still further object of the present invention to provide Gap Diodes fabricated using micromachining techniques in which the separation between electrodes is maintained through the action of piezo-electric,  
20    electrostrictive or magnetostrictive actuators.

An advantage of this invention is that the devices may be constructed inexpensively and reliably.

It is a still further object of the present invention to provide Power Chips and Cool Chips fabricated and operated by MicroEngineeringMechanicalSystems,  
25    or MEMS in which the separation between electrodes is maintained through the action of piezo-electric, electrostrictive or magnetostrictive actuators.

An advantage of this invention is that the devices may be constructed cheaply and reliably.

It is a yet further object of the present invention to provide pairs of  
30    electrodes in which any minor imperfections in the surface of one are replicated in the surface of the other.

An advantage of this invention is that electrodes may be positioned such that the separation between them is of a very small magnitude.

35    An advantage of this invention is that a larger surface area can be used for pumping heat, converting heat to electricity, or any other functions of a diode.

-10-

An advantage of this invention is that benefits accruing to small spaces, such as tunneling effects, can be maximized.

It is a yet further object of the present invention to provide a method of selection of electrode materials in which the thermal expansion coefficient  
5 of the cold side is larger than that of the cold side.

An advantage of this invention is that the temperature difference between the two electrodes can be greatly increased before the electrodes touch each other due to thermal expansion.

#### **Definitions**

10 "Power Chip" is hereby defined as a device which uses a thermal gradient of any kind to create an electrical power or energy output. Power Chips may accomplish this using thermionics, thermotunneling, or other methods as described in this application.

"Cool Chip" is hereby defined as a device which uses electrical power or  
15 energy to pump heat, thereby creating, maintaining, or degrading a thermal gradient. Cool Chips may accomplish this using thermionics, thermotunneling, or other methods as described in this application.

"Gap Diode" is defined as any diode which employs a gap between the anode and the cathode, or the collector and emitter, and which causes or allows  
20 electrons to be transported between the two electrodes, across or through the gap. The gap may or may not have a vacuum between the two electrodes, though Gap Diodes specifically exclude bulk liquids or bulk solids in between the anode and cathode. The Gap Diode may be used for Power Chips or Cool Chips, for devices that are capable of operating as both Power Chips and Cool Chips,  
25 or for other diode applications.

Surface features of two facing surfaces of electrodes "matching" each other, means that where one has an indentation, the other has a protrusion and vice versa. Thus the two surfaces are substantially equidistant from each other throughout their operating range.

#### **Brief Description of Drawings**

30 Figure 1 is a diagrammatic representation of one embodiment of the electrode configuration of a Gap Diode, Power Chip or Cool Chip showing a piezo-electric actuator supporting an electrode.

-11-

Figure 2 is a diagrammatic representation of one embodiment of the electrode configuration of a Gap Diode, Power Chip or Cool Chip, showing piezo-electric actuators at intervals along the under-surface of an electrode.

Figure 3 is a diagrammatic representation of one embodiment of a photoelectric Power Chip with electrode separation controlled by piezo-electric actuators.

Figure 4 is a diagrammatic representation of one embodiment of a device illustrating how heat transfer is facilitated.

Figure 5 is a schematic showing a process for the manufacture of pairs of electrodes that have approximately matching surface details.

It should be noted in all cases that the emitter is the hot side, in a Power Chip, and the collector is the cold side, in a Power Chip. A Cool Chip, however, emits from the cold side, and collects from the hot side. Thus, each thermal interface can be either the hot side or the cold side, depending on whether the device is operating as a Cool Chip, or as a Power Chip.

#### Reference Numerals in Drawings

- 1. Emitter electrode
- 5. Collector electrode
- 10. Region between an Emitter and a Collector
- 15. Housing
- 20. Piezo-electric actuator
- 27. Power supply/Electrical load
- 29. Capacitance controller
- 30. Thermal interface
- 35. Thermal interface
- 40. Connecting wires
- 70. Light beam
- 80. Corrugated sealing tubes
- 82. Metal powder infill

-12-

100. First step

102. Polished monocrystal of first electrode material

110. Second step

112. Layer of material

5 120. Third step

122. Thin layer of second electrode material

130. Fourth step

132. Electrochemically-grown layer of second electrode material

140. Fifth step

## 10 Best Modes for Carrying Out the Invention

The following description describes a number of preferred embodiments of the invention and should not be taken as limiting the invention.

The actuating element is often described as being connected to the collector electrode, however, in some embodiments it could be applied to the emitter  
15 electrode instead.

Referring now to Figure 1, two electrodes 1 and 5 are separated by a region between an emitter and a collector 10 and housed in a housing 15. Electrode 1 is functionally connected to a piezo-electric actuator 20. An electric field is applied to the piezo-electric actuator via connecting wires 40 which  
20 causes it to expand or contract longitudinally, thereby altering the distance of the Region 10 between electrodes 1 and 5. Electrodes 1 and 5 are connected to a capacitance controller 29 which both modifies the piezo actuator 20, and can give feedback to a power supply/electrical load 27 to modify the heat pumping action, and generating action, respectively. The electrodes 1 and 5  
25 are connected to power supply/electrical load 27 via connecting wires 40, which may also be used to connect the electrodes 1 and 5 with capacitance controller 29.

Referring now to Figure 2, two electrodes 1 and 5 are separated by a region 10 and housed in a housing 15. Electrode 1 is attached to a number of piezo-  
30 electric actuators 20 at intervals. An electric field is applied to the piezo-electric actuators via connecting wires 40 which causes them to expand or contract longitudinally, thereby altering the longitudinal distance of

-13-

region 10 between electrodes 1 and 5. Electrodes 1 and 5 are connected to capacitance controller 29 which both modifies the piezo actuator 20, and can give feedback to a power supply/electrical load 27 to modify the heat pumping action, and generating action, respectively. The longitudinal distance of region 10 between electrodes 1 and 5 is controlled by applying an electric field to piezo-electric actuators 20. The capacitance between emitter 1 and collector 5 is measured and controlling circuitry 29 adjusts the field applied to piezo-electric actuators 20 to hold the capacitance, and consequently the distance between the electrodes 10, at a predetermined fixed value. Alternatively the controller may be set to maximize the capacitance and thereby minimize the distance 10 between the electrodes. The diagram shown in Figure 2 can be used as a thermionic device and/or as a tunneling device, and can be used to function as a Power Chip and/or as a Cool Chip. Capacitance controller 29 may be composed of multiple elements, and each piezo actuator 20 may receive its own distinct signal, independent from the control of surrounding elements.

If it is used as a thermionic device, then electrodes 1 and 5 are made from, or are coated with, a thermionically emissive material having a work function consistent with the copious emission of electrons at the temperature of thermal interface 30. The specific work functions can be determined by calculation, or by consulting the art.

When functioning as a Cool Chip, electrons emitted from emitter 1 move across an evacuated space 10 to a collector 5, where they release their kinetic energy as thermal energy which is conducted away from collector 5 through housing 15 to thermal interface 35, which is, in this case, hotter than thermal interface 30 which the electron emission serves to cool.

When functioning as a Power Chip, electrons emitted from emitter 1 move across an evacuated space 10 to a collector 5, where they release their kinetic energy as thermal energy which is conducted away from collector 5 through housing 15 to thermal interface 35, and a current is generated for electrical load 27. The feedback loop from the capacitance controller to the piezo elements allows for the device to adjust for varying conditions, including vibration, shock, and thermal expansion.

When functioning as a tunneling Gap Diode, as one side of the device becomes hot and its components expand, the distance between the electrodes can be maintained at a fixed distance with the feedback loop between capacitance controller 29 and piezo elements 20. Provided the surface of emitter 1 and collector 5 are made sufficiently smooth (or, as discussed below, matching one another), emitter 1 may be moved into such close proximity to collector 5



-14-

that quantum tunneling between the electrodes occurs. As mentioned above, this device can be used as a Gap Diode, a Power Chip, or a Cool Chip. Under these conditions, it is not necessary that region 10 should be evacuated. When the gap distance between the electrodes is in the order of tens of angstroms, thermal conduction through a gas is considerably lessened. In all tunneling embodiments disclosed in this application, this advantage is noted, especially for applications where thermal conduction is a concern, such as Power Chips and Cool Chips. Hence the region 10 is in some embodiments filled with an inert gas.

- 10 When functioning as a diode that is not designed to facilitate heat flow, thermal interface 30 and thermal interface 35, are not necessary, and the resulting device could be integrated into, and used for ordinary diode applications.

- 15 It is to be understood that the term evacuated signifies the substantial removal of the atmosphere between the electrodes, but does not preclude the presence of atoms such as cesium.

- Referring now to Figure 3, which shows in a diagrammatic form a thermal interface 35, electrical connectors 40, and electrical load/power supply 27 for a photoelectric generator embodiment of the device shown in Figure 2. For the sake of clarity, the controlling circuitry comprising connecting wires 40, and capacitance controller 29, and additional connecting wires 40 shown in Figure 2 has been omitted. A light beam 70 passes through housing 15 and impinges on an emitter 1. Emitter 1 is made from, or is coated with, a photoelectrically emissive material having a work function consistent with the copious emission of electrons at the wavelengths of light beam 70. Electrons emitted from emitter 1 move across an evacuated space 10 to a collector 5, where they release their kinetic energy as thermal energy which is conducted away from collector 5 through piezo-electric actuators 20 and housing 15 to thermal interface 35. The electrons return to emitter 1 by means of external circuit 40 thereby powering electrical load/power supply 27. The spacing of region 10 between electrodes 1 and 5 is controlled as described above (see Figure 2). This means that as Power Chip becomes hot and its components expand, the distance between the electrodes can be maintained at a fixed distance. Provided the surface of emitter 1 and collector 5 are made sufficiently smooth, the collector 5 may be moved into such close proximity to emitter 1 that quantum tunneling between the electrodes occurs. Under these conditions, it is not necessary that region 10 should be evacuated, and the device operates as a tunneling Power Chip. It should be noted that a photoelectric Power Chip may use a temperature

-15-

differential, by collecting some of the solar energy in heat form. In this embodiment, the device would function as the Power Chip in Figure 2, the only difference being that the heat energy provided would be solar in origin. The device in Figure 3 may alternatively be primarily photoelectric, where direct photon-electron contact results in the electron either topping the work-function barrier and emitting thermionically, or, in the tunneling version, the incident photon may cause the electron to tunnel. The device may also be a combination of the above, providing any combination of thermionic emission caused by solar heat, thermionic emission caused by direct photoelectric effects, thermotunneling from solar heat, or tunneling emission caused by direct photoelectric effects.

Referring now to Figure 4, which shows a preferred embodiment for facilitating heat transfer between a thermal interface 30 and an electrode 1, corrugated tubes 80, preferably fabricated from stainless steel, form part of the structure between electrode 1 and thermal interface 30. These tubes may be positioned with many variations, and act to allow for the movement of the positioning elements 20 and of the electrode 1 whilst maintaining support, or containment, etc, for the device, by being able to be stretched and/or compressed longitudinally. In some embodiments, corrugated tubes 80 may form the walls of a depository of a metal powder 82, preferably aluminum powder with a grain size of 3-5 microns. More metal powder 82 would be used to receive heat transferred to the collector electrode 1, but the surroundings of the metal powder would be made smaller as the positioning elements 20 would cause the electrode to move upwards. Hence the use of an expandable depository, made from corrugated tubing 80. Corrugated tubes 80 may also enclose the entire device, to allow for movement, as well as individual piezo actuators 20.

For currently available materials, a device having electrodes of the order of 1 x 1 cm, surface irregularities are likely to be such that electrode spacing can be no closer than 0.1 to 1.0  $\mu\text{m}$ , which is not sufficiently close for quantum tunneling to occur. However for smaller electrodes of the order of 0.05 x 0.05 cm, surface irregularities will be sufficiently small to allow the electrodes to be moved to a separation of 5 nm or less, which is sufficiently close for quantum tunneling to occur. It is likely that continued developments in electrodes having smoother surfaces will eventually allow large (1 x 1 cm) electrodes to be brought into close proximity so that electron tunneling may occur. One such approach is illustrated and disclosed in Figure 5, which describes in schematic form a method for producing pairs of electrodes having substantially smooth surfaces in which any topographical features in one are matched in the other. The method involves a first step

-16-

100 in which a polished monocrystal of material 102 is provided. This forms one of the pair of electrodes. Material 102 may also be polished tungsten, or other materials. In a step 110 a thin layer of a second material 112, is deposited onto the surface of the material 102. This layer is sufficiently  
5 thin so that the shape of the polished surface 102 is repeated with high accuracy. A thin layer of a third material 122 is deposited on layer 112 in a step 120, and in a step 130 this is grown electrochemically to form a layer 132. This forms the second electrode. In one preferred embodiment, second material 112 has a melting temperature approximately 0.8 that of first  
10 material 102 and third material 122. In a particularly preferred embodiment, second material 112 is lead and third material 122 is aluminum. In a step 140 the composite formed in steps 100 to 130 is heated up to a temperature greater than the melting temperature of layer 112 but which is lower than the melting temperature of layers 102 and 132. In a particularly preferred  
15 embodiment where second material 112 is lead and third material 122 is aluminum, the composite is heated to about 800K. As layer 112 melts, layers 102 and 132 are drawn apart, and layer 112 is allowed to evaporate completely. In another preferred embodiment, layer 112 may be removed by introducing a solvent that dissolves it, or by introducing a reactive  
20 solution that causes the material to dissolve. This leaves two electrodes 102 and 132 whose surfaces replicate each other. This means that they may be positioned in very close proximity, as is required, for example, for the thermotunnel Power Chip and Cool Chip. In a variation of the method shown in Figure 3, piezoelectric elements may be attached to one or both of the  
25 electrodes 102 and 132 and used to draw the two apart as the intervening layer 112 melts. This ensures that the two electrodes are then in the correct orientation to be moved back into close juxtaposition to each other by the piezoelectric elements.

When considering a Gap Diode wherein the two electrodes are close enough to  
30 one another to allow for electron tunneling to occur, thermal expansion considerations are quite important. If thermal expansion is not taken into account, then the two electrodes could touch, causing the device to fail. The present invention discloses that if the cold side of the Gap Diode has a thermal expansion coefficient larger than that of the hot side, then the risk  
35 of touching is minimized. A preferred embodiment for this selection process, depending on the design temperature ratios of the device, is that the cold side should have a thermal expansion coefficient that is a multiple of the hot side. Specific embodiments include the use of Aluminum on the cold side and Titanium on the hot side. The thermal expansion coefficient of aluminum  
40 is 6 times that of titanium, and it is disclosed that these two materials for

-17-

the electrodes, when combined with the electrode matching invention shown in Figure 5, will tolerate a difference in temperature between the two sides of up to 500 degrees Kelvin.

### Industrial Applicability

5 The essence of the present invention are Power Chips and Cool Chips, utilizing a Gap Diode, in which the separation of the electrodes is set and controlled using piezo-electric, electrostrictive or magnetostrictive or other electroactive positioning elements.

10 Included in this invention is a method for constructing electrodes with matching topologies, the use of thermotunneling to produce a cooling effect, the use of solar energy as the motive energy for Power Chips, the use of small, and angstrom-scale gaps for insulation.

Although the above specification contains many specificities, these should not be construed as limiting the scope of the invention but as merely  
15 providing illustrations of some of the presently preferred embodiments of this invention.

For example, the piezo-electric, electrostrictive or magnetostrictive actuators could be used to position either or both electrodes.

Such actuators, which this invention believes are necessary for accurate  
20 separation between the electrodes of any tunneling Power Chip or tunneling Cool Chip, do not need to be active once the device has been manufactured. For small temperature variations, it is conceivable that the capacitance loop and power supply for the actuators themselves will not be necessary, and the electrodes can be locked into place in the manufacturing or packaging  
25 process. Thus in operation the actuators would not be necessary, as the gap would not be compromised with smaller temperature fluctuations.

In the above specification, capacitance is used to measure the distance between the electrodes. Other methods known in the art may be used, including measuring the tunneling current and optical interferometry. The  
30 generated current produced by a thermionic, thermotunneling or photoelectric Power Chip may also be measured to assess the separation of the electrodes. Other properties that may be measured include heat, for example the temperature of one or both of the electrodes may be used to initiate programmed actuation of the piezo-electric, electrostrictive or  
35 magnetostrictive elements. The position of the electrodes may also be set according to the length of time the device has been in operation. Thus it may be envisaged that the electrodes are set at a certain distance when the

-18-

device is first turned on, and then the positioning of the electrodes is adjusted after certain predetermined time intervals.

In addition, if the inter-converters are constructed using micro-machining techniques, the controlling circuitry for the separation of the electrodes  
5 may be deposited on the surface of the wafer next to the piezo-electric, electrostrictive or magnetostrictive actuators.

Although no specific construction approaches have been described, the devices of the invention may be constructed as MicroElectroMechanicalSystems (MEMS) devices using micro-machining of an appropriate substrate. Integrated circuit  
10 techniques and very large scale integration techniques for forming electrode surfaces on an appropriate substrate may also be used to fabricate the devices. Other approaches useful in the construction of these devices include vapor deposition, fluid deposition, electrolytic deposition, printing, silk screen printing, airbrushing, and solution plating.

15 Substrates that may be used in the construction of these devices are well known to the art and include silicon, silica, glass, metals, and quartz.

Additionally, the active control elements may be pulsed, which will generate AC power output when the device is used as a power generator. The pulsing speeds of piezo elements are well within the requirements necessary for  
20 standard alternating current outputs.

Claims

We claim:

- 1) Apparatus for the conversion of energy, comprising,
  - a) a source of energy for promoting electron tunneling, and,
  - 5 b) an emitter electrode, connected to said source of energy, and,
  - c) a collector electrode, positioned sufficiently close to said emitter electrode for electrons to tunnel from the emitter electrode to the collector electrode, and,
  - 10 d) electrical circuit means, connected to said electrodes, for the circulation of electrons, and,
  - e) manipulating means for controlling the relative electrode positioning, connected to one or both of said electrodes.
- 2) The apparatus of claim 1 further comprising housing means for said apparatus.
- 15 3) The apparatus of claim 2 wherein said housing means is thermally conductive.
- 4) The apparatus of claim 2 wherein said housing means further comprises flexible housing means for the enablement of the movement of said manipulating means and of said electrodes.
- 20 5) The apparatus of claim 2 further comprising thermally conductive metal powder connected to said collector electrode for the transferal of thermal energy.
- 6) The apparatus of claim 5 further comprising an extendable depository for said metal powder, for providing room for the metal powder as the  
25 collector electrode is moved to the area previously occupied by the metal powder.
- 7) The apparatus of claim 1 further comprising control means for assessing the electrode distance, and for actuating said manipulating means based on such assessment.
- 30 8) The apparatus of claim 1 wherein said manipulating means is selected from the group comprising piezo electric, electrostrictive, and magnetostrictive actuators.

-20-

- 9) The apparatus of claim 8 wherein said manipulating means comprises multiple actuators.
- 10) The apparatus of claim 9 comprising means for controlling said multiple actuators independently.
- 5 11) The apparatus of claim 8 wherein said manipulating means is for providing an initial relative electrode positioning of said electrodes.
- 12) The apparatus of claim 11, wherein said manipulating means are not for providing ongoing relative electrode positioning of said electrodes.
- 10 13) The apparatus of claim 1, for the conversion of thermal energy to electrical energy, wherein said source of energy is a source of thermal energy, and said emitter electrode is thermally connected to a source of thermal energy, and wherein said apparatus further comprises heat sink means, thermally connected to said collector electrode, and an electrical load, electrically connected to said collector electrode.
- 15 14) The apparatus of claim 13 wherein said source of thermal energy is of solar origin, wherein solar heat is directed towards said emitter electrode.
- 20 15) The apparatus of claim 1, for photoelectrical electricity generation, wherein said source of energy is a source of photons, directed at said emitter electrode for impacting the electrons in said emitter electrode and for causing said electrons to tunnel to said collector electrode, and wherein said apparatus further comprises an electrical load, electrically connected to said collector electrode, for receiving generated electricity.
- 25 16) The apparatus of claim 15 wherein said source of photons is also a source of thermal energy for providing said electrons in said emitter electrode with additional ability to tunnel to said collector electrode.
- 30 17) Apparatus for the conversion of electrical energy to heat pumping capacity, comprising the apparatus of claim 1, wherein said source of energy comprises an electrical power supply, and further apparatus comprising a heat source and a heat sink, wherein said heat source may be cooler than heat sink, and wherein said heat source is thermally connected to said emitter electrode and said heat sink is thermally connected to said collector electrode, and, means for applying a voltage bias to said electrodes for causing said emitter electrode to emit more
- 35

-21-

electrons via thermotunnelling than the collector electrode emits,  
whereby heat pumping is enabled.

- 18) An electrical generator, comprising the apparatus of claim 1, further  
comprising means for causing the oscillation of said manipulating means,  
5 for the production of alternating current.
- 19) A device for cooling, comprising
- a) a diode, comprising an emitter and a collector electrode, and,
  - b) a substance from which heat is to be removed, and a substance to  
10 which heat is to be transferred, respectively thermally connected  
to said emitter and said collector electrodes, and
  - c) positioning means for spatially positioning at least one of said  
electrodes, relative to the other, and,
  - d) an electrical circuit between said emitter and collector, and,
  - e) means for providing a voltage bias to said emitter so that it  
15 transfers more heat to the collector than the collector transfers  
to the emitter.
- 20) The apparatus of claim 19 wherein said positioning means are selected  
from the group consisting of piezoelectrical actuators, electrostrictive  
actuators, and magnetostrictive actuators.
- 20 21) The apparatus of claim 18 wherein the emitter and collector electrodes  
each have a surface that face each other, wherein said surfaces have  
topographically matching features.
- 22) The apparatus of claim 18 wherein said positioning means is positioned  
in the substantial middle of said collector electrode, and further  
25 comprising housing means for said emitter and collector, wherein said  
housing means comprises corrugated tubing in at least some areas,  
wherein said corrugated tubing is connected to said collector electrode  
to allow said collector to be moved by said positioning means in a  
longitudinal manner, whilst still being housed by said housing means.
- 30 23) A first and a second electrode for use in a diode device, each electrode  
having a surface for positioning facing the other electrode, wherein  
said surfaces are substantially flat and comprise matching topographical  
features to one another.
- 24) A diode device, selected from the group consisting of: thermionic Power  
35 Chips, thermionic Cool Chips, thermo-tunneling Power Chips, thermo-



-22-

tunneling Cool Chips, photoelectric Power Chips, and Gap Diodes, comprising the first and second electrodes of claim 23.

- 25) The diode device of claim 24 wherein said electrodes are positioned closer than 200 angstroms from one another.
- 5 26) The diode device of claim 25 wherein the electrodes are positioned 100 angstroms apart or closer, and wherein an inert gas fills the region between them.
- 10 27) The diode device of claim 24 further comprising manipulating means for controlling the spacing between said electrodes, wherein said manipulating means is selected from the group consisting of: electroactive, magnetostrictive, electrostrictive, and piezo-electric means.
- 28) The two electrodes of claim 23 in which the electrodes have differing thermal expansion coefficients.
- 15 29) The two electrodes of claim 28 wherein one electrode is for higher temperature operation than the other electrode, and said electrode for higher temperature operation has a lower thermal expansion coefficient than said other electrode.
- 20 30) The two electrodes of claim 29 wherein the ratio of said thermal expansion coefficients is greater than four to one.
- 31) The two electrodes of claim 29 wherein said electrode for higher temperature operation is composed of titanium.
- 32) The two electrodes of claim 29 wherein said other electrode is composed of aluminum.
- 25 33) A method for making the pair of electrodes of claim 23, said method comprising the steps of:
- a) fabricating a first electrode with a substantially flat surface,
- b) coating said surface of said first electrode with a thin, uniform layer of a first material,
- 30 c) coating said layer of said first material with a layer of a second material suitable for use as a second electrode, and,
- d) separating said first electrode and said first and second materials from one another, in a manner non-destructive to said first electrode and said second material, whereby said third material is

-23-

suitable for use as a second electrode, and comprises matching topographical features to said first electrode.

- 34) The method of claim 33 further comprising the steps of:
- a) positioning said electrodes less than 100 angstroms apart
  - 5 b) adding an inert gas to the region between said electrodes to thermally insulate the electrodes from one another.
- 35) The method of claim 33 in which said first material is removed by a process selected from the group consisting of: heating to a temperature greater than that of the melting temperature of said first material but
- 10 lower than the melting temperature of said first electrode and of said second material, so as to evaporate said first material, introducing a solvent to dissolve said first material, introducing a reactive solution which reacts with said first material and dissolves it, and applying a vacuum to pump out any materials except said first electrode and said
- 15 second material, or a combination of the above processes.
- 36) The method of claim 33 additionally comprising the steps of:
- a) attaching said first electrode and said second material to controllable positioning means,
  - b) and using said controllable positioning means to effect a

20 separation between said first electrode and said second material in the separating step

  - c) so that topographical features on the surface of said first electrode are maintained in spatial orientation with said matching topographical features on said second electrode.
- 25 37) A thermal insulator for thermally insulating two surfaces from one another, comprising an inert gas enclosed in a gap of between 1 and 100 angstroms thickness between said two surfaces, and further comprising a manipulating means selected from the group consisting of electroactive, magnetostrictive, electrostrictive, and piezo-electric means, wherein
- 30 the manipulating means is connected to one or both of said surfaces and is for controlling the distance of the surfaces from one another.
- 38) Apparatus for pumping heat, comprising
- a) a diode, the emitter of said diode being in thermal contact with a mass from which heat is to be removed, a collector of said diode

35 being in thermal contact with a mass to which heat is to be carried, and

-24-

- b) a supply of electrical power for supplying current at a suitable voltage to said diode, wherein said emitter and collector are positioned close enough to one another to allow substantial electron tunneling from said emitter to said collector, and wherein  
5 there is a gap between said emitter and said collector.
- 39) The apparatus of claim 38 wherein said gap contains a vacuum.
- 40) The apparatus of claim 38 wherein said gap contains inert gas molecules.
- 41) A method for pumping heat, comprising:
- 10 a) a step of forming an emitter electrode  
b) a step of forming a collector electrode  
c) a step of connecting each electrode to electric power means and thermal transfer means  
d) a step of bringing said electrodes to within 200 angstroms of each other, to allow electrons to tunnel between said electrodes  
15 e) a step of applying a suitable voltage bias to said electrodes to pump heat from said emitter electrode to said collector electrode.
- 42) In a heat pumping system: emitter means having an emitter face; collector means having a collector face; housing means structured to hold said emitter and collector faces with close spacing between them;  
20 said close-spacing being no more than 200 angstroms distance to allow for electron thermotunneling from said emitter means to said collector means.

Fig. 1

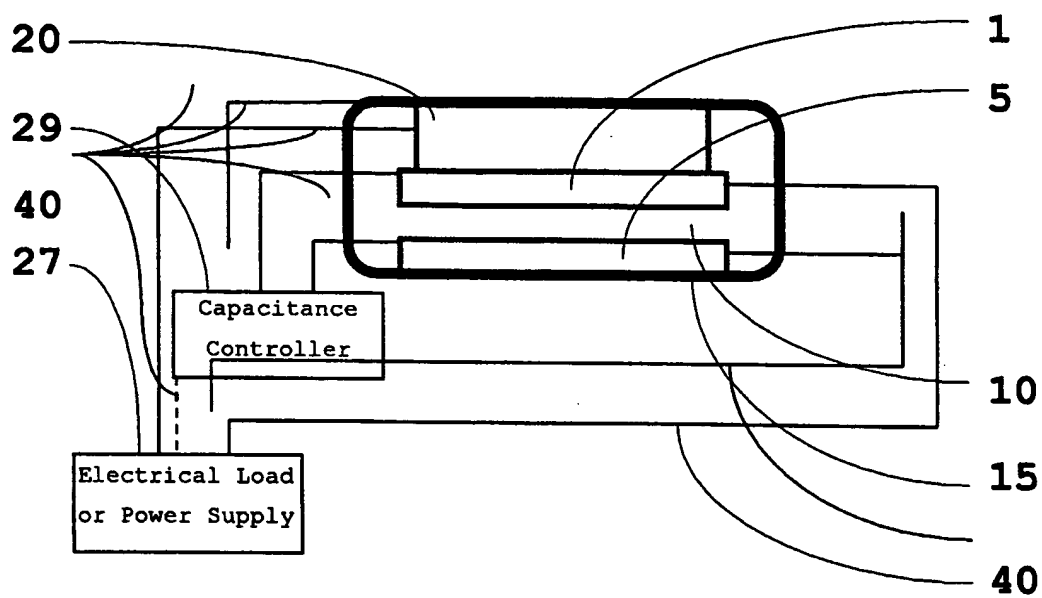


Fig. 2

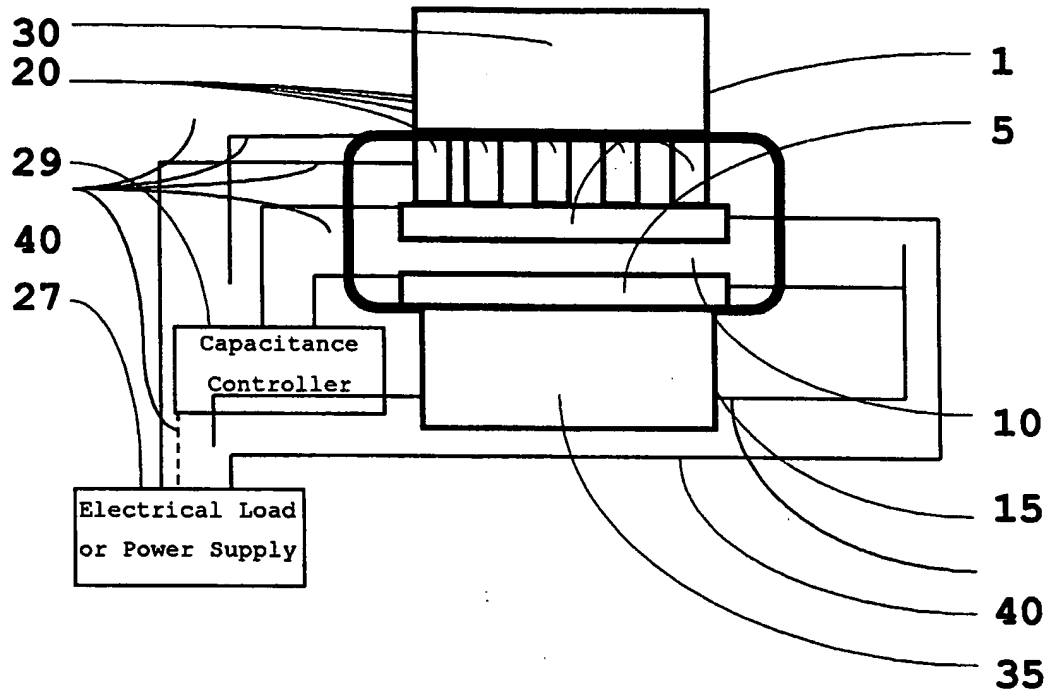


Fig. 3

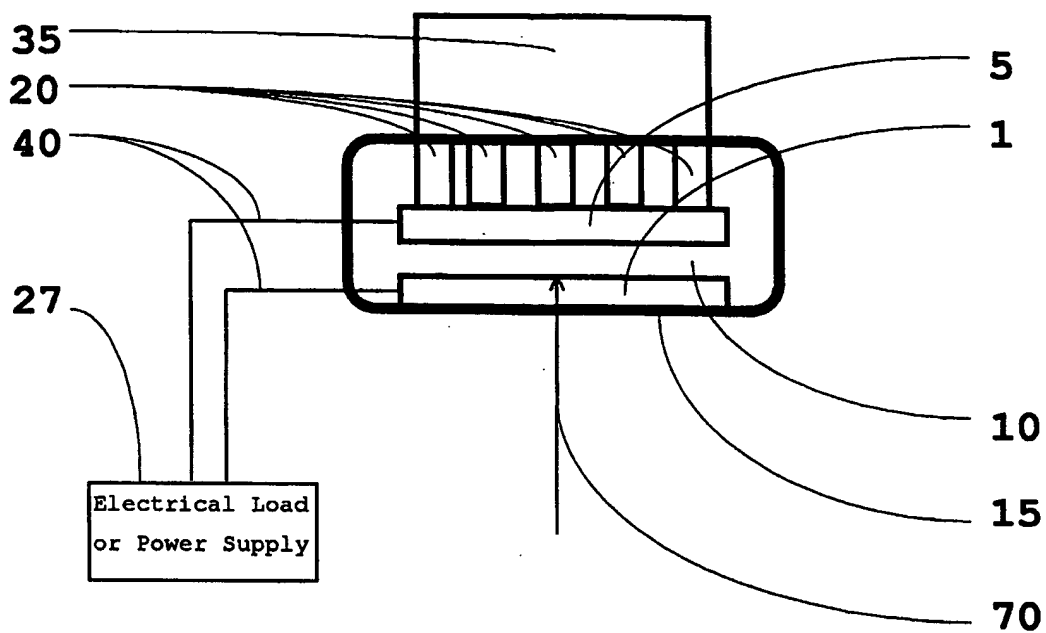


Fig. 4

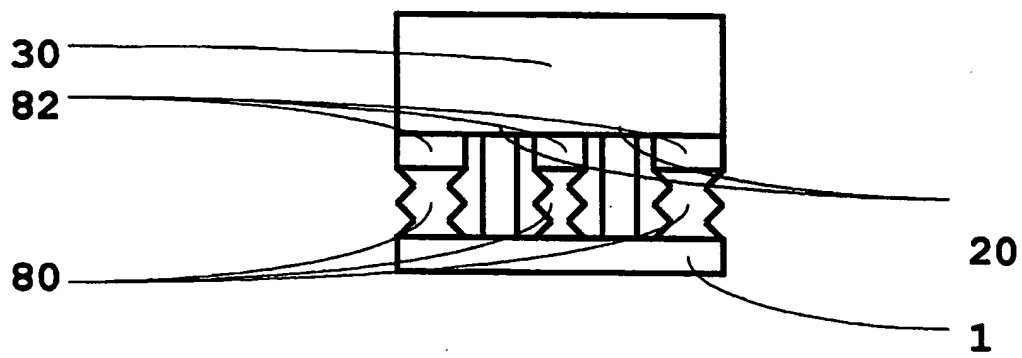
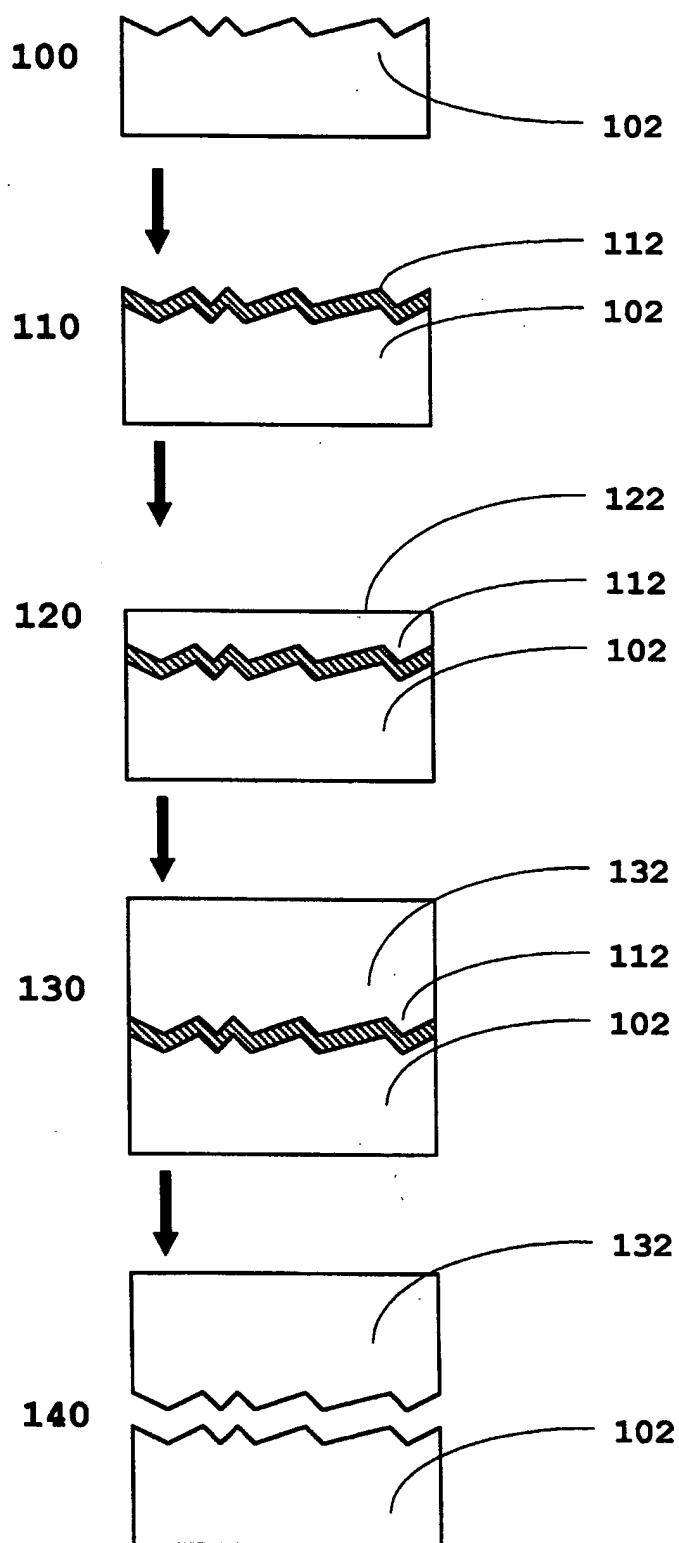


Fig. 5





# INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US98/18645

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H02N2/00; 3/00

US CL : 310/306, 307; 136/205; 62/3.1; 165/104.23; 322/2R

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 310/306, 307; 136/205; 62/3.1; 165/104.23; 322/2R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

STN, GPCI

search terms: thermoelectric, thermionic, actuator, generator, piezoelectric, electrode

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,722,242 A (EDELSON) 03 March 1998 (03.03.98), columns 8-10	19, 23, 24, 25, 28, 29, 38, 39, 41, 42
X	US 5,675,972 A (Edelson) 14 OCT 1997 (14.10.97), col. 5 lines 5-60	19 and 38
A	US 4,039,352 A (MARINESCU) 02 August 1977 (02.08.77), see entire document	1-42
A	US 5,699,668 A(COX) 23 December 1997 (23.12.97), see entire document	1-42

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search

16 DECEMBER 1998

Date of mailing of the international search report

21 JAN 1999

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